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Performance enhancement of DCMLI fed DTC-PMSM drive in electric vehicle

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ABSTRACT

This paper focus on the simulation and hardware analysis of a diode clamped multilevel inverter (DCMLI) fed direct torque control (DTC) permanent magnet synchronous motor (PMSM) drive in electric vehicle (EV) application. DTC-PMSM drive is more used for torque and speed control. The existing DTC PMSM drive consists of torque and flux hysteresis comparators and suffers from variable switching frequency and torque ripples. These problems can be solved by using carrier-based space vector modulation (CBSVM) about torque and flux. In this proposed approach a DCMLI fed 4 poles, 0.5 HP DTC PMSM drive system is designed and simulated using carrier-based CBSVM. Simulation and experimental implementation are carried out in MATLAB environment and AVR Microcontroller respectively. The simulated performances are studied in steady-state and transient conditions for varying load, speed, and torque. The results of the DTC-PMSM drive system using CBSVM show that the proposed method can effectively reduce the torque ripple and maintain a constant speed and also improved driving performance of drive for electric vehicle applications.

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1. INTRODUCTION

The permanent magnet synchronous motor (PMSM) drive has the heart of electric vehicle application. The main advantages of PMSM are high power-to-weight ratio, high efficiency, ruggedness, low value of cogging torque, and the capacity of the additional reluctance torque as compared to the induction machine. It is not a necessity to supply magnetizing currents through the stator flux because of magnets in the rotor and the constant air gap. The motor is exposed to different load and speed profiles in the electric vehicle application. This paper finds its motivation, at low speeds and the back emf respectively. So gives high speed as in high input current. For reducing the switching losses, it would operate at low switching frequencies and high switching frequencies for low speeds and high speeds respectively. Vector control is the most, simple and efficient method [1].

In ac drives, the direct torque control (DTC) method has a replacement for the field oriented control (FOC) method due to its high performance and was invented in 1980 [2]. The main advantages of DTC are robustness, simple construction, fast torque response, and current regulation also no need for coordinate

transformation [3]. For high power applications, and diode clamped multilevel inverters (DCMLI) are most commonly used [4]. Due to the disadvantages of the conventional inverter, it is switched over to a multilevel inverter. Multilevel inverters have the advantage of lower dv/dt per switching, lower voltage distortion, less harmonic content, and operate at high efficiencies [5]. They can switch to a lower frequency than pulse width modulation (PWM) controller inverters [6]. Hence a novel DTC-based diode clamped multilevel inverter (DCMLI) fed PMSM drive with carrier-based space vector modulation (CBSVM) switching technique has been proposed for automotive applications which can decrease current ripple and maintain the switching frequency [7]. To removes some of the drawbacks present in DTC, different modulation techniques have been proposed [8]. In support vector machine (SVM), active vectors are chosen from the look-up table and the zero vectors by a duty-ratio controller [9].

The DTC is a good controller of flux and torque control for PMSM in steady-state and transient-state [10]. In DTC, without the need for coordinate transformation, current regulator, PWM signal generator, and position sensors, the principle works on the selection of voltage vectors strategy [11]. The main advantages & disadvantages of DTC are stator current control and disadvantages are current ripples, variable switching frequency, and torque and flux control [12]. The multilevel inverter is proposed to solve the problems [13].

In DTC-SVM the estimator is used to calculate an appropriate voltage vector to compensate for flux and torque errors which gives less torque and flux ripple but introduces more complexity and losses [14]. To overcome this drawback in space vector pulse width modulation (SVPWM), a novel modulation technique named CBSVM is described using the method of effective time [15]. In this method output voltage of the inverter is directly calculated and the voltage modulation task can be greatly simplified [16]. The time relocation algorithm can be used for output signals of each inverter arm converted in a simple form [17]. Therefore, the main objective of this paper is to introduce three-level DCMLI-fed DTC- PMSM drives using CBSVM [18]. The simulation is carried out in a MATLAB environment and experimentally verified using an AVR microcontroller which incorporates Atmega8 for switching purposes & Atmega16 is used for monitor &control [19].

Section 1 described the introduction. Section 2 described the mathematical modeling of PMSM. Section 3 described the proposed methodology. Section 4 described simulation results analysis of DTC-PMSM with CBSVM, in section 5, hardware analysis was made. In section 6 conclusions have been given.

2. MATHEMATICAL MODEL

The induced voltage in the D-axis winding:

$$u_d = R_d i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \tag{1}$$

where *'id'* and *'Rd'* are called direct-axis stator current and resistance respectively. The induced voltage in the Q-axis winding:

$$u_q = R_q i_q + \frac{d\lambda_q}{dt} - \omega_r \lambda_d \tag{2}$$

where *'Rq'* and '*iq*' are called the quadrature-axis resistance and current of the stator

$$\lambda_d = L_d i_d + \lambda_m \tag{3}$$

where λd=flux-linkage in the direct-axis of the stator in webers, λm is the PM rotor flux

$$\lambda_q = L_q i_q \tag{4}$$

where λq=flux-linkage in the quadrature-axis stator *(Wb)*, in this case of the quadrature-axis, there are no magnets so λm is absent, for round rotor PMSM

$$L_d = L_q \tag{5}$$

The PMSM torque equation is:

$$T_e = \frac{3}{2}\frac{p}{2}(\lambda_d i_q - \lambda_q i_d) \tag{6}$$

substituting for *'λd'* and *'λq'* in the torque equation of PMSM,

$$T_e = \frac{3}{2}\frac{p}{2}[(\lambda_d i_d + \lambda_m) i_q - L_q i_q i_d] \tag{7}$$

$$T_e = \frac{3}{2}\frac{p}{2}[(L_d - L_q) i_d i_q + \lambda_m i_q] \tag{8}$$

the two components of torque developed are:

$$Reluctance\ torque = \frac{3}{2}\frac{p}{2}(L_d - L_q) i_d i_q \tag{9}$$

$$field\ torque = \frac{3}{2}\frac{p}{2}\lambda_m i_q \tag{10}$$

$$T_e = \frac{3}{2}\frac{p}{2}\lambda_m i_q \tag{11}$$

In a round rotor PMSM, the electromagnetic torque present is the field torque present due to the PM flux linkage, λm. For a chosen PMSM, the PM rotor flux-linkage *(λm)* and the number of poles (*p*) are constant. Hence, the electromagnetic torque equation for the round-rotor PMSM is

$$T_e = Kt\, i_q \tag{12}$$

where *Kt=Torque constant*

$$K_t = \frac{3}{2}\frac{p}{2}\lambda_m \tag{13}$$

therefore, electromagnetic torque is

$$T_e = T_l + B\,\omega_m + J\,\frac{d\omega_m}{dt} \tag{14}$$

3. PROPOSED METHODOLOGY

3.1. Direct torque control

Figure 1 shows the schematic diagram of the DCMLI -DTC PMSM drive. In DTC, select stator voltage vectors directly by hysteresis stator flux and torque control. Stator flux Ψ_s^* and torque T_e^* are compared by the hysteresis comparators for selection of voltage vector in inverter by switching table [20].

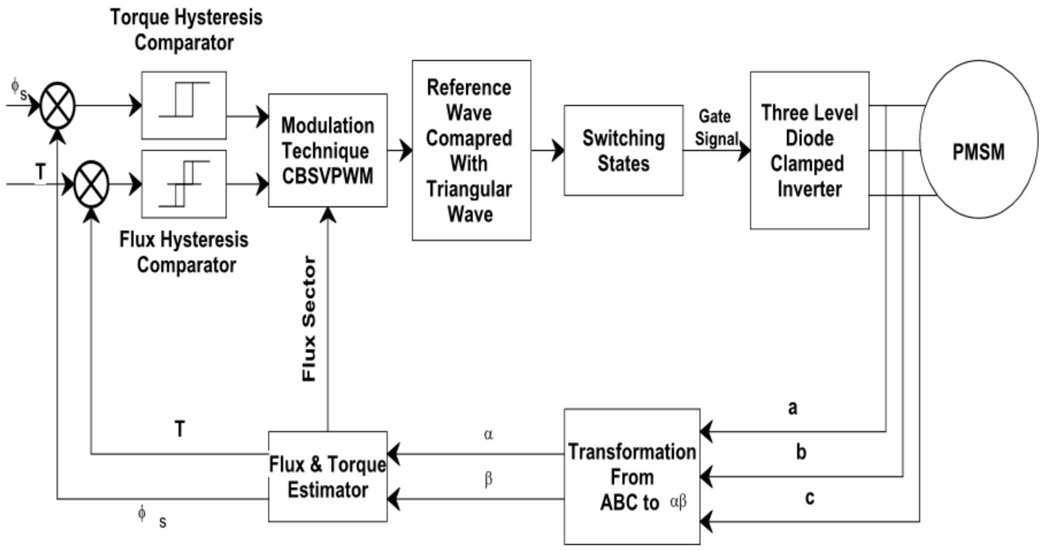


Figure 1. Schematic of DCMLI-DTC PMSM drive

For selecting an appropriate voltage vector, hysteresis, and comparators are replaced by an estimator for torque and flux errors measurements. It gives less torque and flux ripple for getting a good dynamic performance and also gives simplicity, introduces more complexity, and loses DTC. A novel CB-SVM is introduced. It has the advantages require effective time and the inverter output voltage is directly calculated fewer times for voltage modulation task simplification [21]. The less time algorithm can be used to deduce actual gating signals for each inverter arm in a simple form. Using Clark transformation, the measured motor currents are transformed to α-β. The voltage is calculated from the inverter switching state into α-β reference frame for the DC-link voltage. The inverter output voltage is directly calculated and converted in a simple form in less time by the time relocation algorithm in the proposed DTC- CBSVM PMSM drive [22].

4. SIMULATION RESULTS

4.1. Steady-state performance of DTC-PMSM drive

The D & Q axis inductances are 0.0068H and 0.0068H, the values of resistance, and permanent flux are 1.9Ω and 0.15Wb. The total number of the pole is 2, the values of friction and movement of inertia for PMSM are 0.000059 Nm-s; and 0.00021 kgm^2. The dc-link voltage is 380V. The sampling time and frequency are 0.0004 sec and 2.5 kHz for 3Nm constant load torque at a reference speed of 1200 rpm.

The output voltage of DCMLI line voltage and the three-phase stator current using CBSVM are purely sinewave in Figure 2 and Figure 3 respectively with few high-order harmonics to the steady operation [23]. Figure 4 to Figure 7 shows the performance of the DTC-PMSM drive using CBSVM in a steady-state condition. In Figure 4, At time t=1s, the reference speed stepped from 0 to 1200 rpm, in the range of t=2 sec to 4 sec, speed is almost constant. In the range of t=4 sec to 4.5 sec. The speed has been in the range of 1200 rpm to 1500 rpm. Rotor speed was near 1500 rpm and the motor goes in a steady operation due to the speed controller quickly exited saturation. At time t=4.5 sec motor speed reached the reference value with the highest acceleration and torque, as shown in Figure 5. The load torque is added in the range of (0-5N.m) at 1sec and is suddenly decreased in the range of (5-4N.m) at 2 sec as shown in Figure 5. It can be seen that the motor torque change as per the motor load. The change in the value of the system was only 0.2% and zero at the steady value. At the time 0.02 s to 0.07 s, the motor voltage reaches 500 V, and in the time range of 0.08 s to 1 s, the motor voltage fall. Initially motor current is very high. It reaches 200 amp. At the time t=1 s, it reduces and again reaches to constant 200 amp up to 8 sec. Figure 8 shows that flux response of DTC-PMSM drives using CBSVM. Figures 9, 10(a) and (b), 11 shows the performance of the DTC-PMSM drive using CBSVM in transient conditions. Figure 12 and Figure 13(a)-(c) shows that the THD of DCMLI line voltage and current using CBSVM. Table 1 shows the DCMLI THD outputs. Table 2 shows torque ripple & copper loss analysis of DTC-PMSM drive using CBSVM at 2.5 kHz switching frequencies.

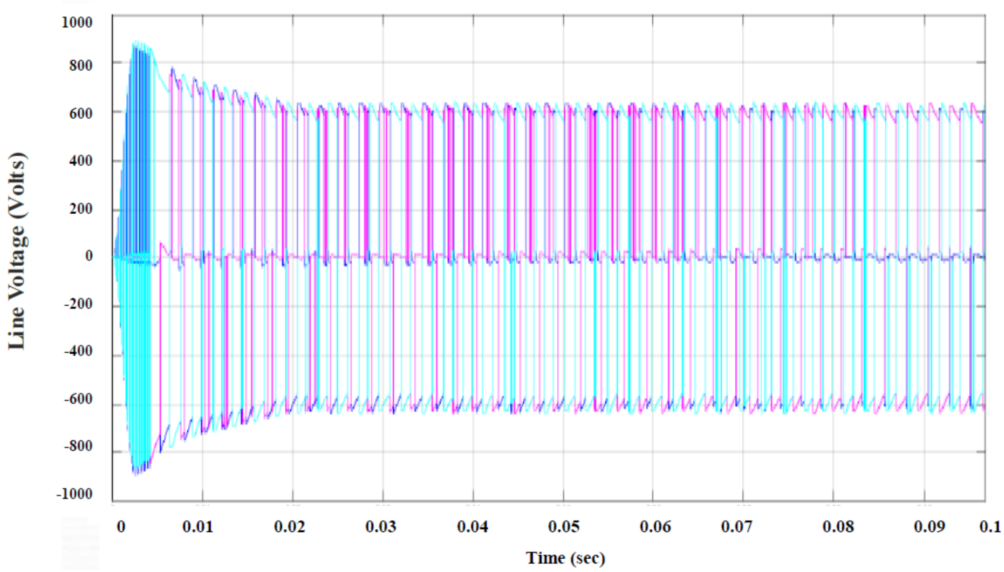


Figure 2. DCMLI line voltage waveform using CBSVM

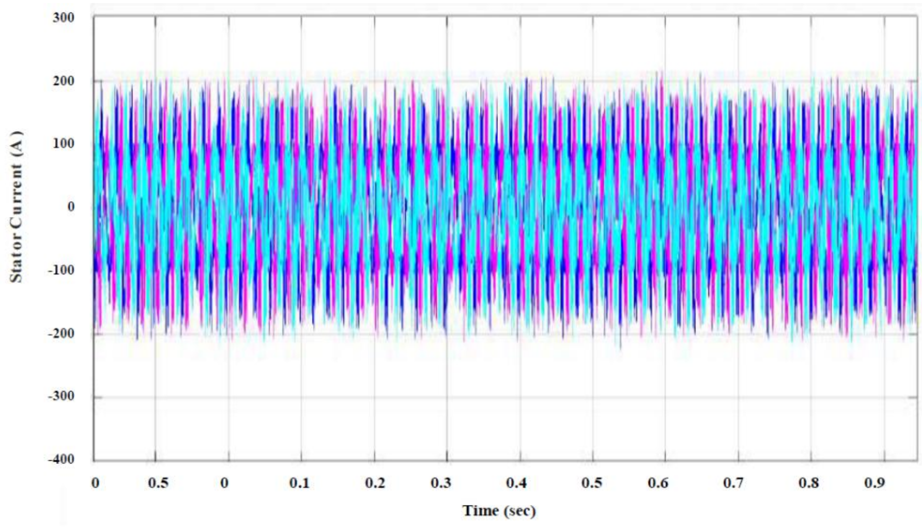


Figure 3. DCMLI current waveform using CBSVM

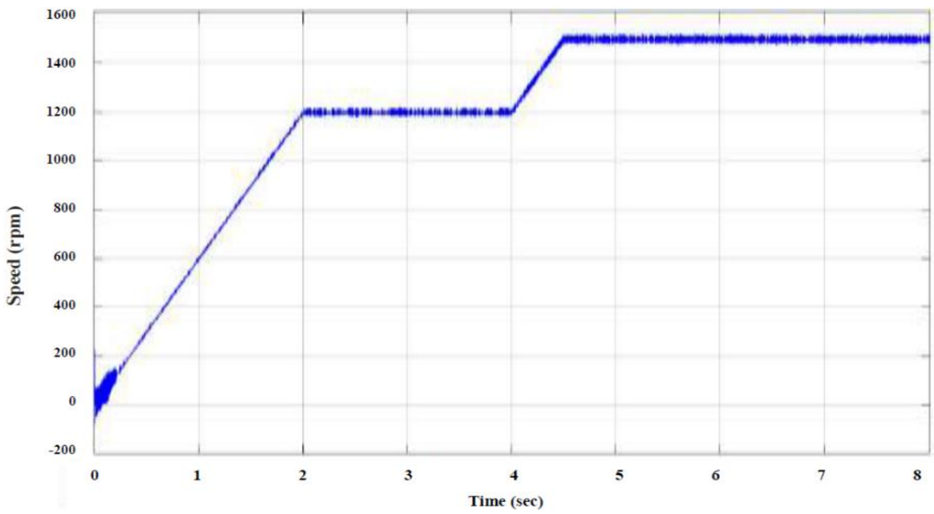


Figure 4. Speed analysis of DTC-PMSM drive

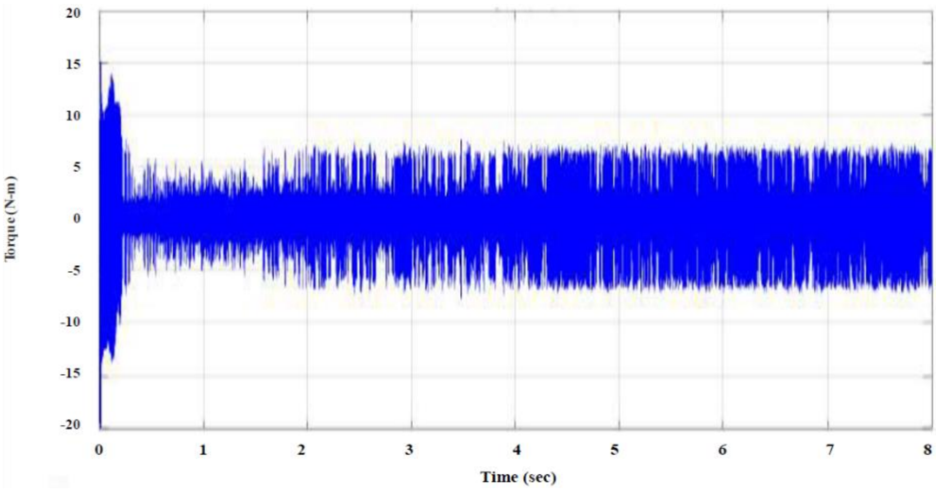


Figure 5. Torque analysis of DTC-PMSM drive

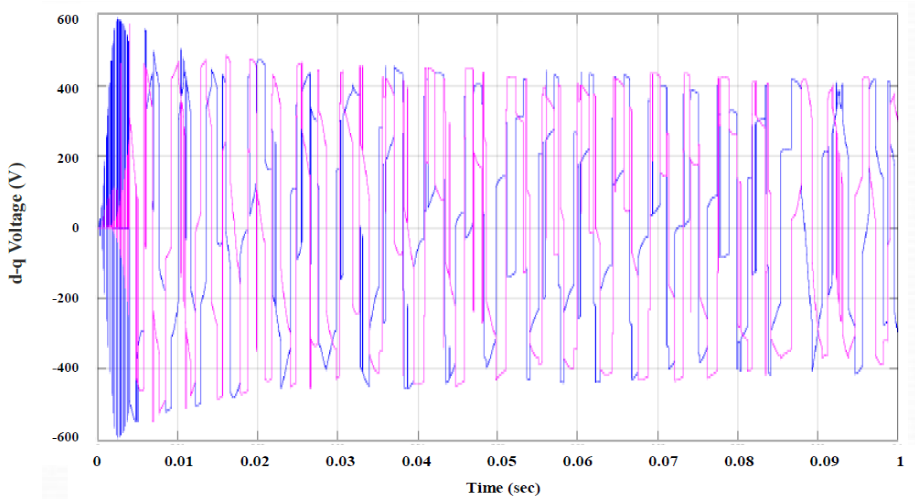


Figure 6. The motor voltage of DTC-PMSM drive

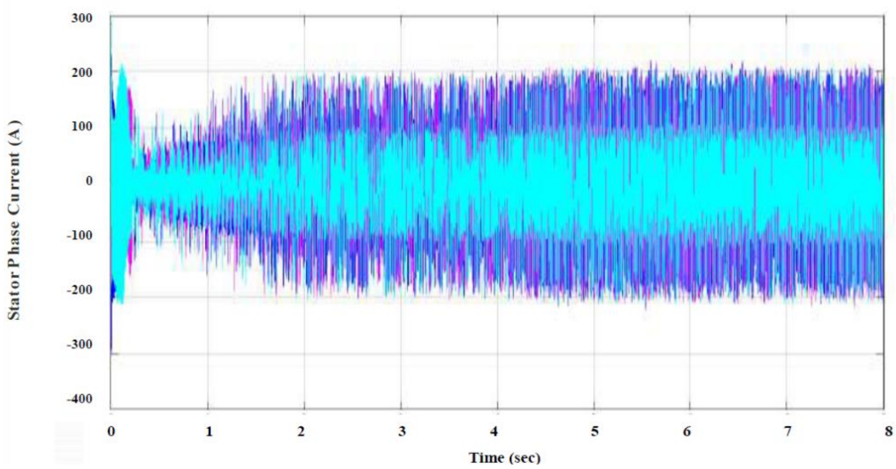


Figure 7. Stator's current analysis of DTC-PMSM drive using CBSV

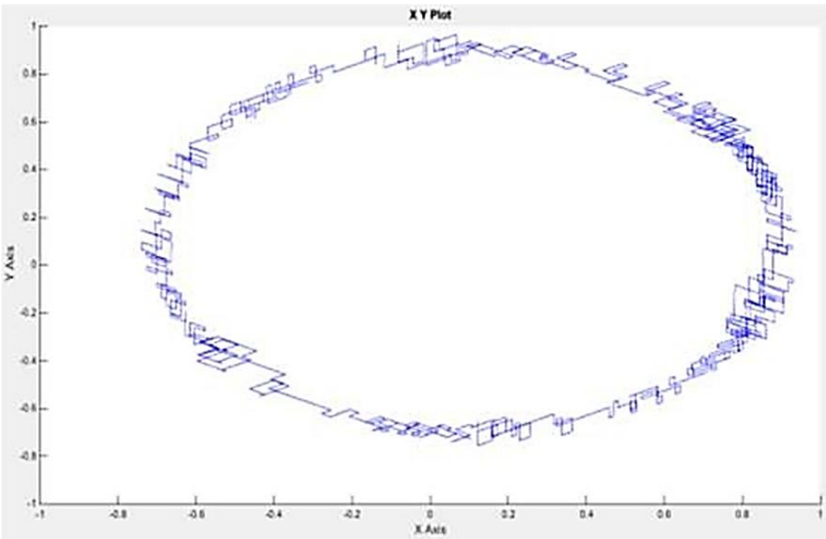
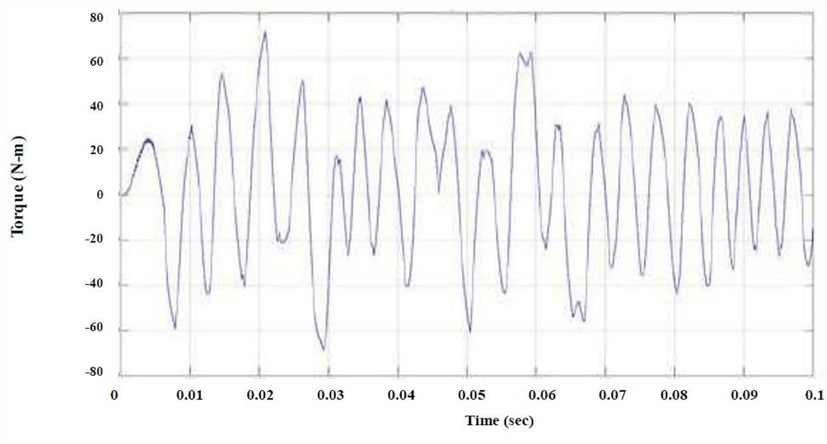


Figure 8. Flux analysis of DTC-PMSM drive

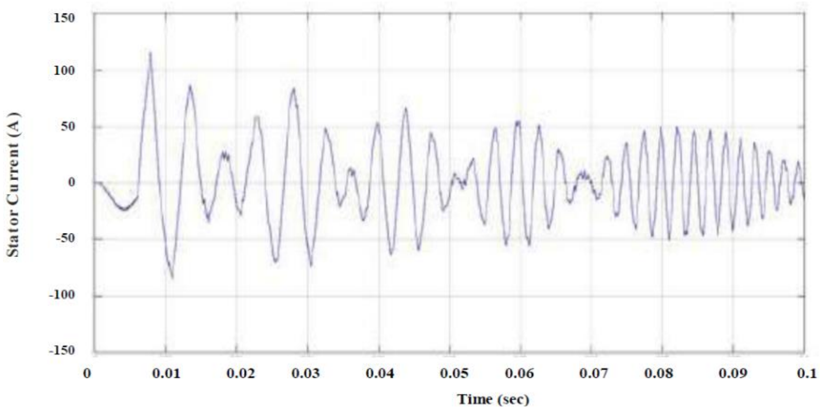
4.2. Transient performance of DTC-PMSM drive

4.2.1. Transient performance of DTC-PMSM drive at load (3N-M)

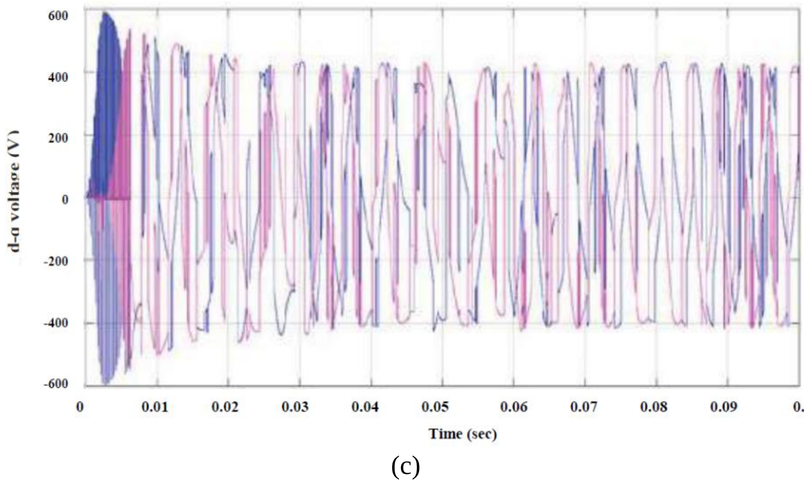
Figure 9 shows transient performance of DTC-PMSM drives. Figure 9(a) shows the starting torque at 3 or 4 times its nominal value for the desired speed. Figure 9(b) shows the d-q motor voltage. It increases up to 600V and constant at 400V. Figure 9(c) shows the stator current. Initially motor takes more currents and it is constants at particular speed [24].



(a)

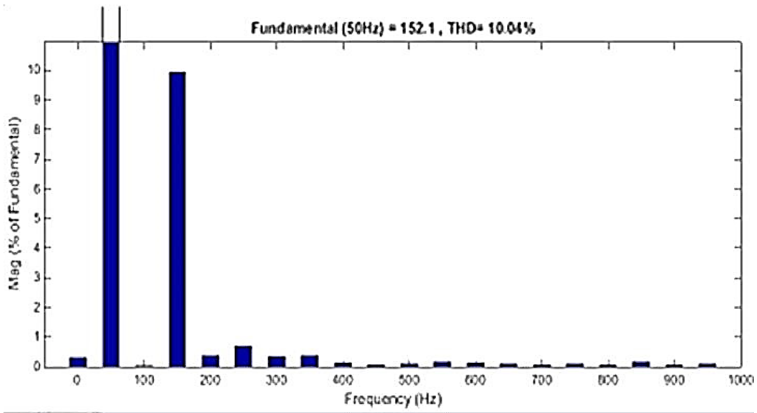


(b)

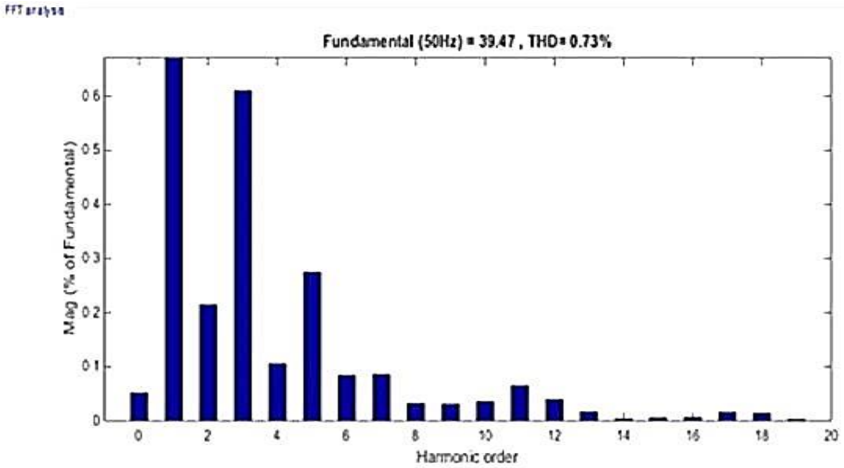


(c)

Figure 9. Transient performance of DTC-PMSM drives for; (a) transient performance of torque analysis (b) transient performance of motor voltage, and (c) transient performance of stator current analysis



(a)t



(b)

Figure 10. DCMLI THD (a) Voltage output and (b) Current output

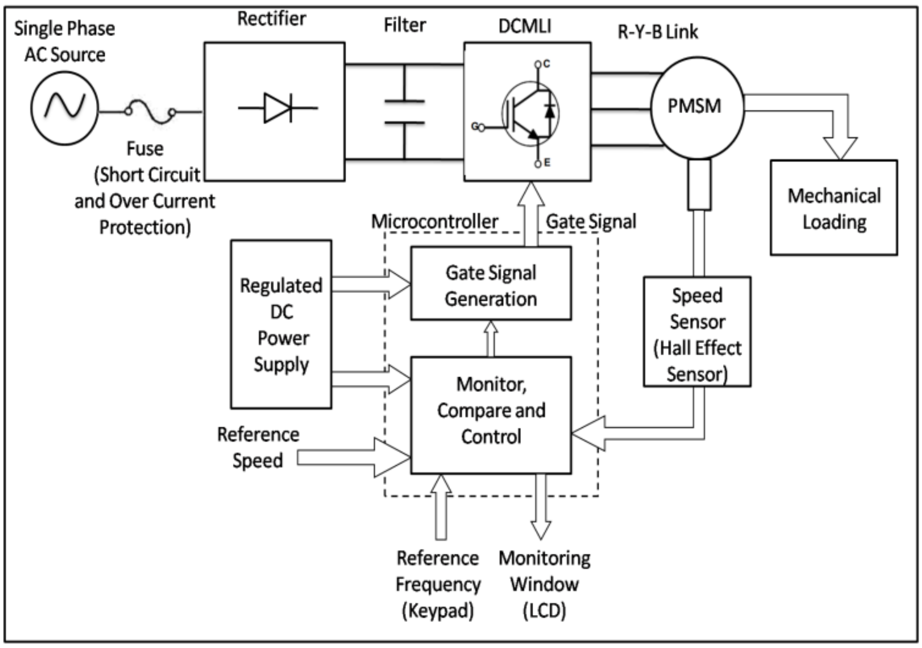


Figure 11. Block diagram of DCMLI-DTC PMSM drive using CBSVM

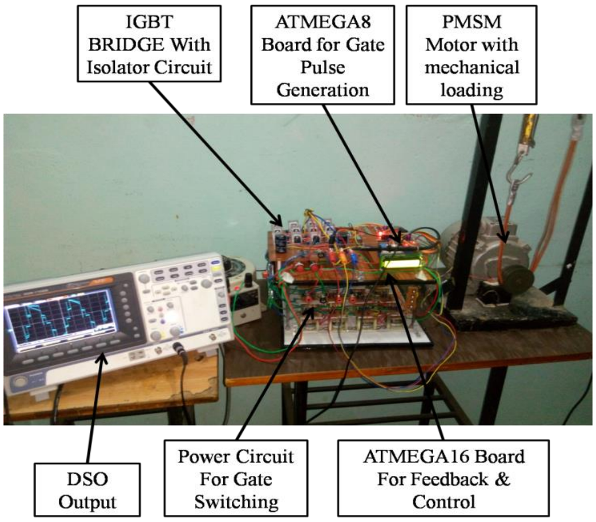
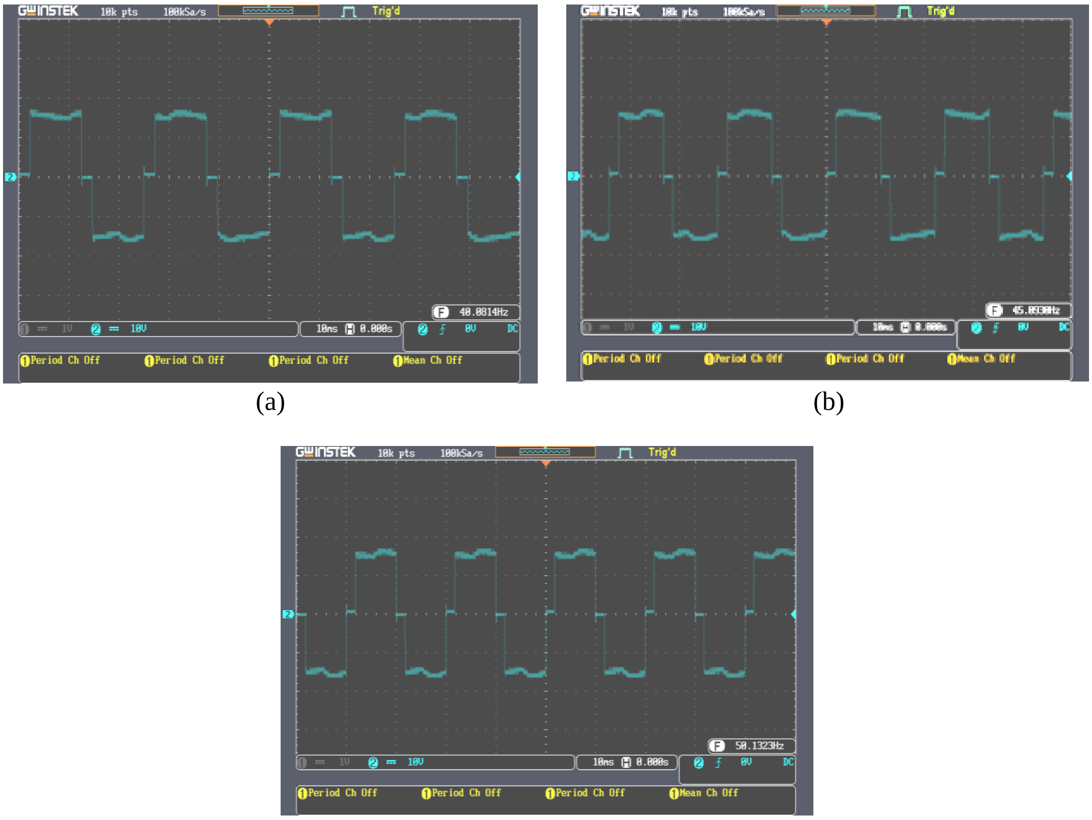


Figure 12. Experimental setup of DCMLI-DTC PMSM drive using CBSVM



(a) (b)

(c)

Figure 13. phase voltages (a) at 40 Hz (b) at 45 Hz, and (c) at 50 Hz

Table 1. DCMLI THD analysis

THD	CBSVM (%)
Line voltage	10.04
Line current	0.73

From the simulation analysis, we calculate the % torque ripple and copper loss in watts by using the formula $p_{cu}=(Ia^2+Ib^2+Ic^2)$ x R), assume $Ra=Rb=Rc$=Torque ripple (%)=($Tmax-Tmin$)/ $Tavg*$ 100.

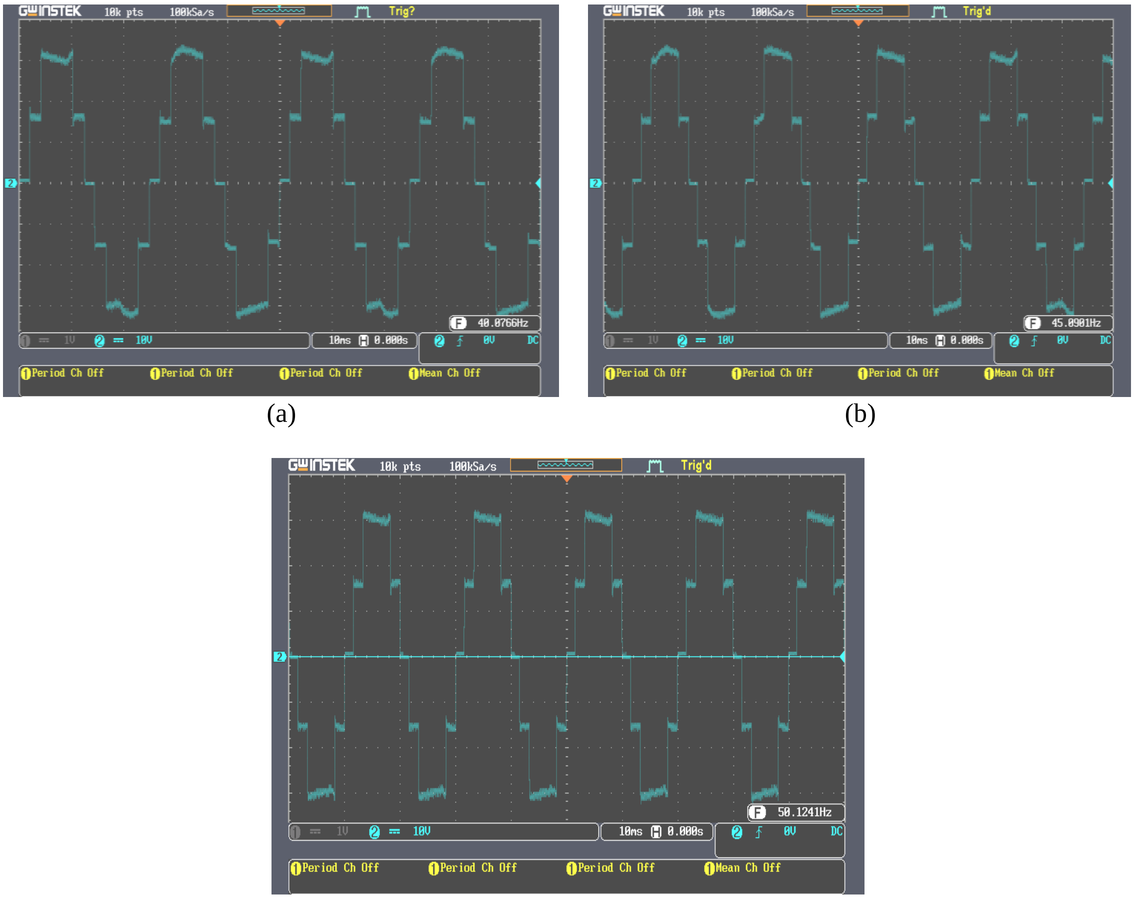
Table 2. Torque and copper loss analysis

Speed (RPM)	Switching frequency (kHz)	%Torque ripple	PCU in watt
1200-1500 rpm	2.5 KHz	10.52	36.19W

5. HARDWARE IMPLEMENTATION

For triggering the Insulated-gate bipolar transistor (IGBT), twelve gate pulses generate by using a diode clamped inverter. The hardware consists of AVR microcontroller, optocouplers (4N35), and FGA15N120AN IGBT drivers. Figure 11 shows the schematic diagram of the hardware model. The generation of twelve pulses for IGBT's power circuit by using AVR microcontroller programmed. Port B and Port C are assigned to generate pulses for the inner and outer IGBTs. 4N35 optocouplers have been used for the protection of high and low-voltage devices. Voltage and Power to switch on and off the IGBTs, IGBT's driver FGA15N120AN has been used. Generation of pulses using the CBSVM technique for DCMLI by The AVR Microcontroller The hardware setup of the DCMLI -DTC PMSM drive using CBSVM is shown in Figure 12. The converter is designed for the following specifications: Input voltage=280 V (rms), supply frequency=50 Hz, rectifier voltage with filter=380 V dc, Inverter voltage=270 V (line-line) switching frequencies=2.5 KHz, inverter power=1.5 KVA, load power-1.8 KW (resistive) [25].

The hardware results are presented for DTC- CBSVM PMSM drives as shown in Figures 13, 14(a)-(c), 15. Hence, we conclude that by increasing the inverter frequency the speed of the motor also gets increased [26]. At constant frequency, the motor speed also remains constant, irrespective of the load. The output voltage using the CB-SVM scheme is better than using the SVM scheme [27]. Torque verse load power characteristics at different frequencies are shown in Figures 16(a)-(c). Load-motor speed variation at a different frequency shows in Tables 3-5 respectively [28].



(a) (b) (c)

Figure 14. Line voltages (a) at 40 Hz (b) at 45 Hz, and (c) at 50 Hz

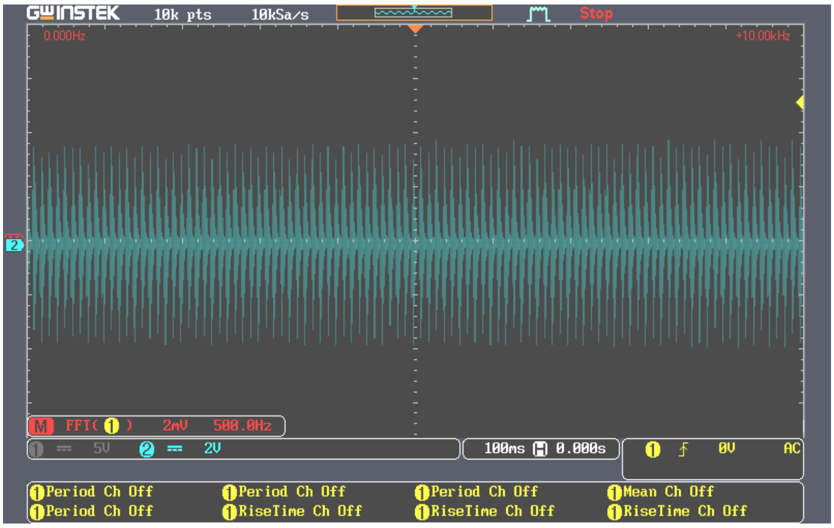


Figure 15. Inverter current at 50 Hz

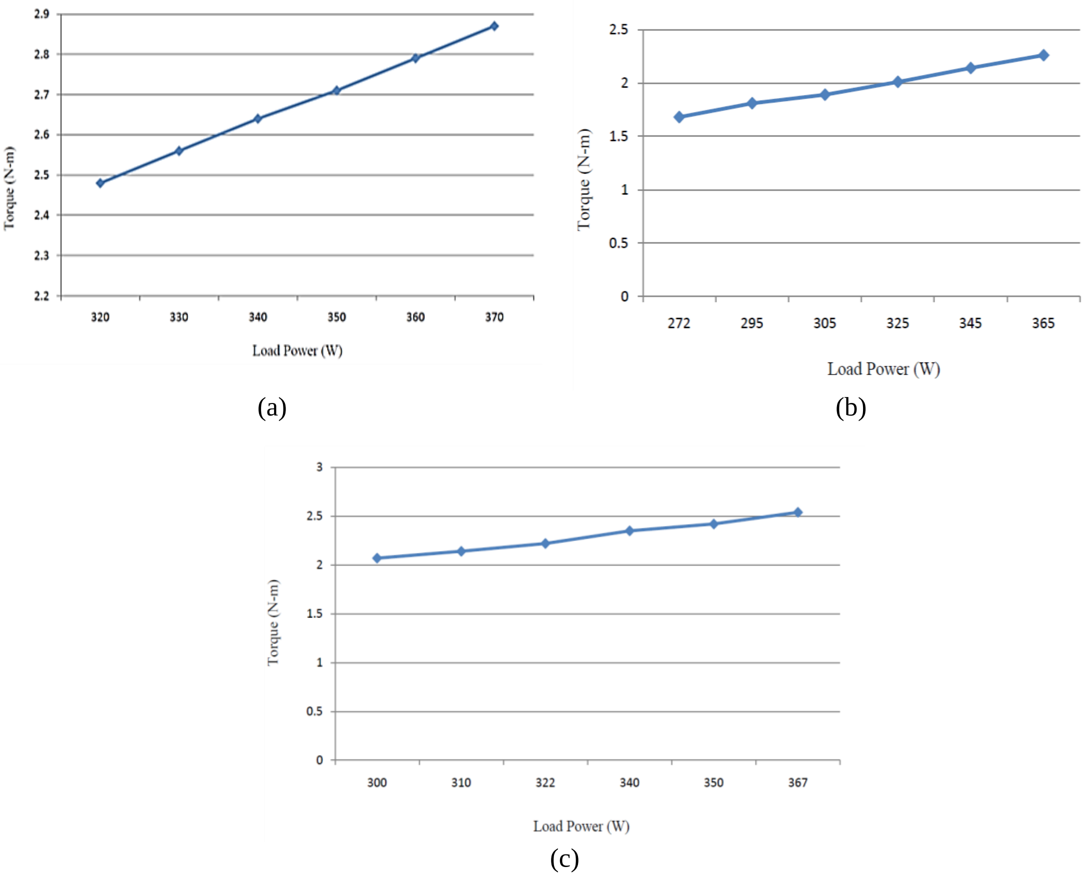


Figure 16. torque vs load power characteristics (a) at 1200 rpm, (b) at 1350 rpm, and (c) at 1500 rpm

Table 3. Load-motor speed variation at 40 Hz

Sr. No.	Weight (Kg)	Volt (V)	Current (A)	Power (W)	Torque (N-m)	Expected speed (rpm)	Measured speed (rpm)
1	0.5	260	1.23	320	2.48	1200	1240
2	1.0	260	1.26	330	2.56	1200	1240
3	1.5	260	1.30	340	2.64	1200	1240
4	2.0	260	1.34	350	2.71	1200	1240
5	2.5	260	1.38	360	2.79	1200	1240
6	3.0	260	1.42	370	2.87	1200	1240

Table 4. Load-motor speed variation at 45 Hz

Sr. No.	Weight (Kg)	Volt (V)	Current (A)	Power (W)	Torque (N-m)	Expected speed (rpm)	Measured speed (rpm)
1	0.5	264	1.13	300	2.08	1350	1380
2	1.0	264	1.13	300	2.08	1350	1380
3	1.5	264	1.17	310	2.15	1350	1380
4	2.0	264	1.21	320	2.22	1350	1380
5	2.5	264	1.25	330	2.29	1350	1380
6	3.0	264	1.25	330	2.29	1350	1380

Table 5. Load-motor speed variation at 50 Hz

Sr. No.	Weight (Kg)	Volt (V)	Current (A)	Power (W)	Torque (N-m)	Expected speed (rpm)	Measured speed (rpm)
1	0.5	270	1.01	272	1.68	1500	1540
2	1.0	270	1.09	295	1.81	1500	1540
3	1.5	270	1.13	305	1.89	1500	1540
4	2.0	270	1.20	325	2.01	1500	1540
5	2.5	270	1.28	345	2.14	1500	1540
6	3.0	270	1.35	365	2.26	1500	1540

It is observed that, at a constant frequency, speed remains constant irrespective of load. The motor runs at synchronous speed. Speed also gets changed accordingly to the inverter frequency. The overall motor performance can be very well judged from the performance characteristic shown in Figures 17(a)-(c), 18(a)-(c).

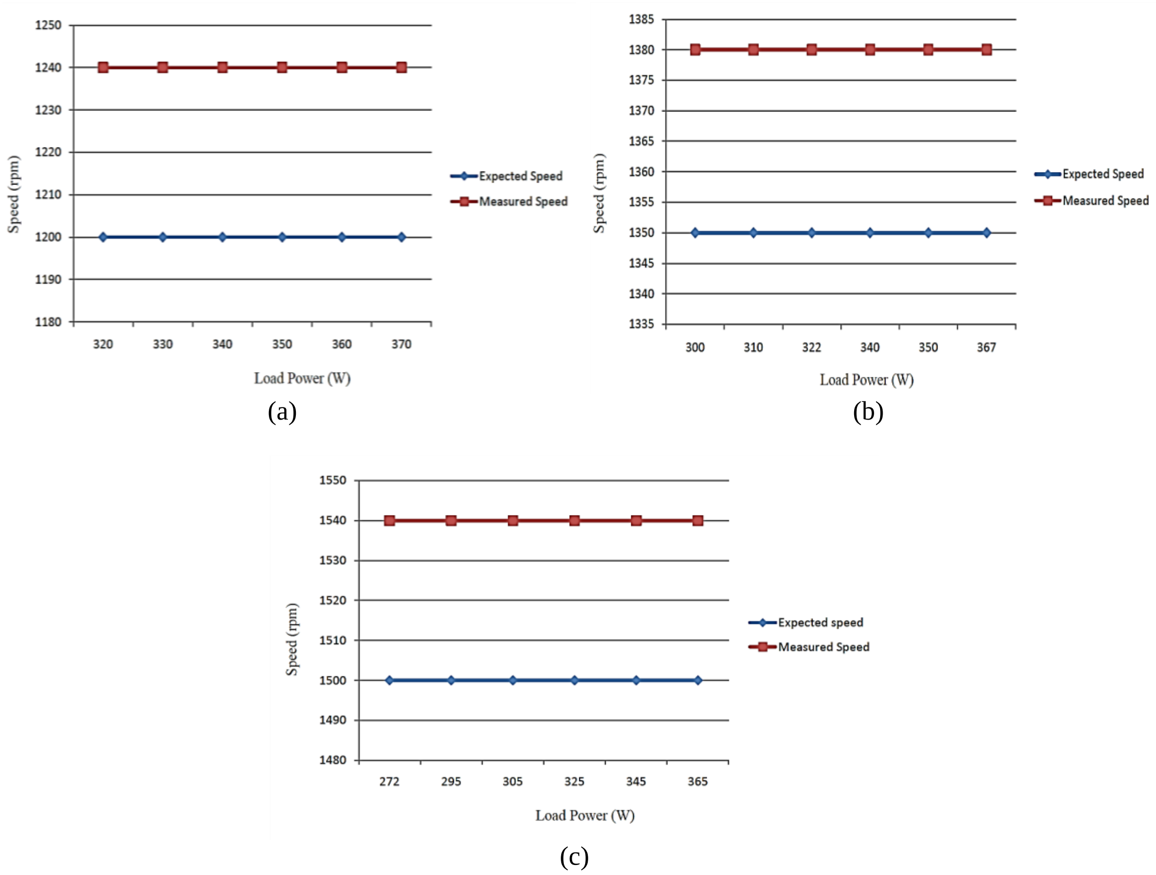


Figure 17. Speed vs load power characteristics (a) at 1200 rpm (b) at 1350 rpm and (c) at 1500 rpm

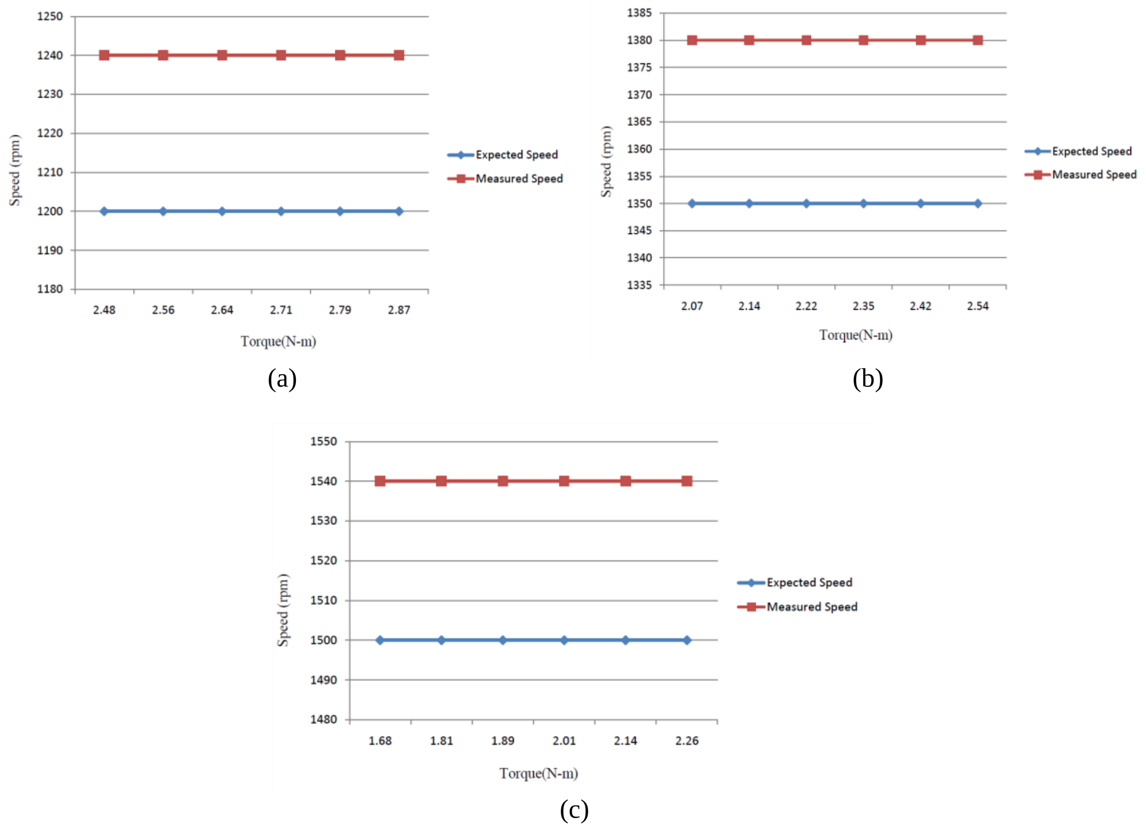


Figure 18. Speed vs torque characteristics (a) at 1200 rpm, (b) at 1350 rpm, and (c) at 1500 rpm

5. CONCLUSION

The simulation and experimental analysis of a DTC-CBSVM PMSM drive in an electric vehicle (EV) has been discussed in this paper. The inverter output voltage is directly calculated and converted in a simple form in less time by the time relocation algorithm in the proposed PMSM drive. In DTC-CBSVM PMSM drive, it can effectively reduce the torque ripple and maintain a constant speed. In the novel, the DTC-CBSVM method, torque ripple, and harmonic distortion reductions in motor currents and voltages are shown. Hence driving performance of the PMSM drive can be improved for electric vehicle applications.

REFERENCES

[1] I. Takahashi and T. Noguchi, “A new quick-response and high-efficiency control strategy of an induction motor,” *IEEE Transactions on Industry Applications*, vol. IA-22, no. 5, pp. 820–827, Sep. 1986, doi: 10.1109/TIA.1986.4504799.

[2] M. Depenbrock, “Direct self-control (DSC) of inverter-fed induction machine,” *IEEE Transactions on Power Electronics*, vol. 3, no. 4, pp. 420–429, Oct. 1988, doi: 10.1109/63.17963.

[3] T. G. Habetler, F. Profumo, M. Pastorelli, and L. M. Tolbert, “Direct torque control of induction machines using space vector modulation,” *IEEE Transactions on Industry Applications*, vol. 28, no. 5, pp. 1045–1053, 1992, doi: 10.1109/28.158828.

[4] I. G. Bird and H. Zelaya De La Parra, “Fuzzy logic torque ripple reduction for DTC based AC drives,” *Electronics Letters*, vol. 33, no. 17, p. 1501, 1997, doi: 10.1049/el:19970967.

[5] D. Casadei, G. Serra, and A. Tani, “Improvement of direct torque control performance by using a discrete SVM technique,” in *PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196)*, 1998, vol. 2, pp. 997–1003, doi: 10.1109/PESC.1998.703125.

[6] P. K. Steimer, J. K. Steinke, and H. E. Gruning, “A reliable, interface-friendly medium voltage drive based on the robust IGCT and DTC technologies,” in *Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370)*, vol. 3, pp. 1505–1512, doi: 10.1109/IAS.1999.805941.

[7] Kyo-Beum Lee, Joong-Ho Song, Ick Choy, and Ji-Yoon Yoo, “Torque ripple reduction in DTC of induction motor driven by three-level inverter with low switching frequency,” *IEEE Transactions on Power Electronics*, vol. 17, no. 2, pp. 255–264, Mar. 2002, doi: 10.1109/63.988836.

[8] L. Romeral, A. Arias, E. Aldabas, and M. G. Jayne, “Novel direct torque control (DTC) scheme with fuzzy adaptive torque-ripple reduction,” *IEEE Transactions on Industrial Electronics*, vol. 50, no. 3, pp. 487–492, Jun. 2003, doi: 10.1109/TIE.2003.812352.

[9] G. S. Buja and M. P. Kazmierkowski, “Direct torque control of PWM inverter-fed AC Motors—A survey,” *IEEE Transactions on Industrial Electronics*, vol. 51, no. 4, pp. 744–757, Aug. 2004, doi: 10.1109/TIE.2004.831717.

[10] G. Brando and R. Rizzo, “An optimized algorithm for torque oscillation reduction in DTC-induction motor drives using 3-level NPC inverter,” in *2004 IEEE International Symposium on Industrial Electronics*, 2004, vol. 2, pp. 1215–1220 vol. 2, doi:

10.1109/ISIE.2004.1571986.

[11] Y. C. Zhang and Z. M. Zhao, “Study on capacitor voltage balance for multi-level inverter based on a fast SVM algorithm,” in *Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering*, 2006, vol. 26, no. 18, pp. 71–76.

[12] B. P. Panigrahi, D. Prasad, and S. SenGupta, “A simple hardware realization of switching table based direct torque control of induction motor,” *Electric Power Systems Research*, vol. 77, no. 2, pp. 181–190, Feb. 2007, doi: 10.1016/j.epsr.2006.02.015.

[13] A. Gharakhani and A. Radan, “Analytical study of affecting characteristic of voltage vectors of a three-level NPC inverter on torque and flux of DTC controlled drives,” in *2007 IEEE International Electric Machines & Drives Conference*, May 2007, vol. 1, pp. 754–759, doi: 10.1109/IEMDC.2007.382762.

[14] J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, “Multilevel voltage-source-converter topologies for industrial medium-voltage drives,” *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 2930–2945, Dec. 2007, doi: 10.1109/TIE.2007.907044.

[15] R. Shriwastava, S. Deshmukh, A. Tidke, and M. Thakre, “Comparative evaluation of control techniques of PMSM drive in automotive application,” *Journal of Physics: Conference Series*, vol. 2062, no. 1, p. 012024, Nov. 2021, doi: 10.1088/1742-6596/2062/1/012024.

[16] X. Li and G. Chen, “Harmonic suppression technology of three-phase diode rectifier based on third harmonic current injection,” in *2007 European Conference on Power Electronics and Applications*, 2007, pp. 1–9, doi: 10.1109/EPE.2007.4417760.

[17] G. Abad, M. A. Rodriguez, and J. Poza, “Two-level VSC based predictive direct torque control of the doubly fed induction machine with reduced torque and flux ripples at low constant switching frequency,” *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1050–1061, May 2008, doi: 10.1109/TPEL.2008.921160.

[18] M. P. Thakre and N. Kumar, “Evaluation and control perceptive of VSM-based multilevel PV-STATCOM for distributed energy system,” *MAPAN*, vol. 36, no. 3, pp. 561–578, Sep. 2021, doi: 10.1007/s12647-021-00481-x.

[19] S. Busquets-Monge, S. Alepuz, J. Bordonau, and J. Peracaula, “Voltage balancing control of diode-clamped multilevel converters with passive front-ends,” in *2007 IEEE International Symposium on Industrial Electronics*, Jun. 2007, pp. 544–549, doi: 10.1109/ISIE.2007.4374655.

[20] Yongchang Zhang, Zhengming Zhao, Ting Lu, and Liqiang Yuan, “Sensorless 3-level inverter-fed induction motor drive based on indirect torque control,” in *2009 IEEE 6th International Power Electronics and Motion Control Conference*, May 2009, pp. 589–593, doi: 10.1109/IPEMC.2009.5157455.

[21] M. K. Sahu, B. P. Panigrahi, and A. K. Panda, “A utility friendly direct torque control technique of three-phase induction motor with two-level inverter using 180-degree conduction mode,” *International Journal of Engineering Science and Technology (IJEST)*, vol. 3, no. 5, pp. 4120–4130, 2011.

[22] S. Saravanan, P. Usha Rani, and M. P. Thakre, “Evaluation and improvement of a transformerless high-efficiency DC–DC converter for renewable energy applications employing a fuzzy logic controller,” *MAPAN*, Jan. 2022, doi: 10.1007/s12647-021-00530-5.

[23] R. G. Shriwastava, “Sensorless field-oriented control of PMSM drive system for automotive application,” *International Journal of Electric and Hybrid Vehicles*, vol. 8, no. 3, p. 213, 2016, doi: 10.1504/IJEHV.2016.080015.

[24] R. G. Shriwastava, D. R. Bhise, and P. Nagrale, “Comparative analysis of FOC based three level DCMLI driven PMSM drive,” in *2019 International Conference on Innovative Trends and Advances in Engineering and Technology (ICITAET)*, Dec. 2019, pp. 26–31, doi: 10.1109/ICITAET47105.2019.9170242.

[25] S. S. Hadpe, R. G. Shriwastava, S. B. Patil, and M. P. Thakre, “The architecture of a 24 pulse dynamic voltage restorer for voltage enhancement incorporating vector control methodologies,” *SSRN Electronic Journal*, 2021, doi: 10.2139/ssrn.3883846.

[26] M. P. Thakre and A. Ahmad, “Interline power flow controller (IPFC) deployment in long transmission lines and its effects on distance relay,” *Journal of The Institution of Engineers (India): Series B*, vol. 103, no. 2, pp. 491–505, Apr. 2022, doi: 10.1007/s40031-021-00637-y.

[27] M. P. Thakre and P. S. Borse, “Analytical evaluation of FOC and DTC induction motor drives in three levels and five levels diode clamped inverter,” in *2020 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)*, Dec. 2020, pp. 1–6, doi: 10.1109/ICPECTS49113.2020.9337015.

[28] M. P. Thakre and N. P. Matale, “Alleviation of voltage sag-swell by DVR based on SVPWM technique,” in *2020 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)*, Dec. 2020, pp. 1–6, doi: 10.1109/ICPECTS49113.2020.9336972.

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